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High-Power Millimeter-Wave Rotary Joint for Radar Applications

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Abstract—**The rotary joint is a useful microwave component that connects a fixed part to a rotatable part. This study analyzes the effect of the discontinuity on the interface of a rotary joint for several waveguide modes. Simulation results indicate that the transmission of the TE_{01} mode is independent of the geometry of the joint, and thus is ideal for such application. A rotary joint consisting of two identical TE_{01} mode converters, clasped each other by a bearing, is designed, fabricated, and tested. Back-to-back transmission measurements exhibit an excellent agreement to the results of computer simulations. The measured optimum transmission is 97% with a 3-dB bandwidth of 8.5 GHz, centered at 35.0 GHz. The cold measurement shows that the results are independent of the angle of rotation. In addition, a high-power experiment is conducted. The just developed rotary joint can operate up to a peak input power of 210 W with a duty of 18%. The working principle, although demonstrated in the millimeter-wave region, can be applied up to the terahertz region where the joint gap is generally critical except for the operating TE_{01} mode.**

I. INTRODUCTION AND BACKGROUND

Microwave rotary joint that connects a stationary part to a rotatable part is an essential device for tracking radar applications. A good rotary joint is characterized by high transmission, low reflection, broad bandwidth, and high-power capability. Varieties of rotary joints have long been invented and are commercially available in coaxial and waveguide forms. However, few studies have addressed on the effect of the joint gap. The shape of the gap significantly affects the performance of a rotary joint. It is especially critical in the millimeter-wave or even the terahertz region where the gap effect is significant.

Azimuthal symmetry of the field pattern is preferred to ensure rotatable features. It exists in the TEM mode, the circularly polarized TE_{mn} modes, TM_{0n} modes, and TE_{0n} modes. The selection of the operating mode depends on how easily the desired mode is excited. Thus TEM, TE_{11}, and TM_{01} modes are generally chosen. The surface current of the TE_{01} mode is polarized in the azimuthal direction and has low transmission loss, suggesting that the TE_{01} mode is a good candidate for rotary joint application since no surface current flows across the gap. Recently, a high-performance TE_{01} mode converter was reported. Therefore, a rotary joint is constructed herein using two identical TE_{01} mode converters joining back-to-back by a simply sliding contact.

This work presents a rotary joint based on the TE_{01} mode converter with the emphasis on the effect of the joint gap. The gap geometry between two converters and the effect of mis-alignment is analyzed in detail. The principle and design are presented. A cold test using a vector network analyzer and a hot test using high-power millimeter-wave source are to be presented.

II. RESULTS

Figure 1(a) displays the design drawings of the rotary joint under study. It comprises a pair of mode converters that are joined with a bearing. Each converter is made of oxygen-free high-conductivity (OFHC) copper with a slotted plate (part A) and a plane cover (part B or C). Two identical converters are joined back-to-back through a uniform middle section of length 3.0 cm. The slotted plate is machined using a computer numerically controlled (CNC) lathe with a tolerance of 0.01 mm. Each converter is aligned with pins and fastened with screws. In the test, two converters are joined back-to-back, which allows a direct measurement to be made using a two-port vector network analyzer (VNA, Agilent 8510C) as shown in Fig. 1(b). A well-calibrated two-port VNA is adopted.

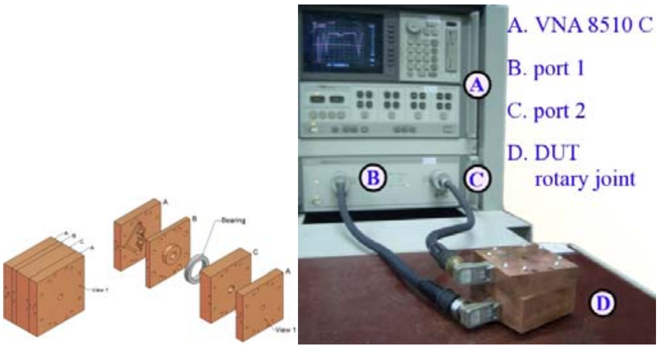

Figure 1 (a) Design drawing of the rotary joint - two converters joined back-to-back with a bearing. (b) Cold test setup. The measured circuit is calibrated. The rotary joint can rotate freely.

The radius of the circular waveguide is 6 mm. The cutoff frequencies for the first six modes, TE_{11}, TM_{01}, TE_{21}, TM_{11}, TE_{01}, and TE_{31}, are 14.7, 19.1, 24.3, 30.5, 30.5, and 33.4 GHz, respectively. Therefore, when the desired TE_{01} mode is being excited, the concentration of the other five modes shall be kept as low as possible. The arrangements of the sidewall couplings prevent the excitations of TM waves. Additionally, the quad-feed structure is unfavorable to TE_{11}, TE_{21}, and TE_{31} modes. Instead, it is suitable for generating a four-fold or a circular symmetric field pattern. Therefore, high mode purity is expected.

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A. Back-to-back measurement

Figure 2(a) shows the simulated back-to-back transmission for five different angles of rotation. The angle of rotation is defined in the inset. The angle θ between the two identical converters can be adjusted freely. Simulation results demonstrate that the transmission is independent of the orientation of the two mode converters. The measured results, as shown in Fig. 2(b), are highly consistent with the HFSS simulation data. The bandwidths associated with the 1-dB and 3-dB transmission losses are 5.7 GHz and 8.5 GHz, respectively. The measured converting efficiency of a single converter is about 98.5%. The ohmic loss and the reflection account for the other 1.5%.

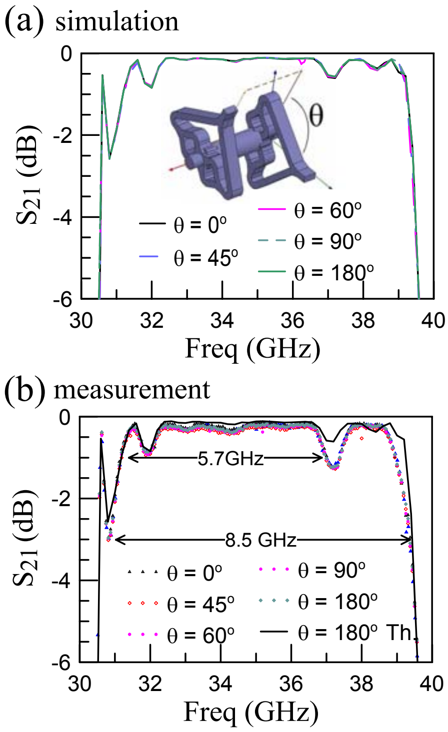

Figure 2 Cold test of the rotary joint. (a) Simulated transmission for five different angles. (b) Measured and simulated results. The measured results agree well with the simulation.

B. High-power test

Figure 3(a) schematically depicts the experimental setup for the high-power test. An Extended Interaction Klystron Amplifier (EIKA or EIA) is used to provide an adjustable power source. The output power and duty are controlled by the input signal, which is generated by a solid-state amplifier and a signal generator. An isolator is used to protect the EIA from the damaging reflected wave. The incident and transmitted powers are measured using a power meter. The transmitted power is dumped to a high-power water load. In the experiment, the rotary joint rotates freely.

Figure 3(b) shows the measured results. The transmission at high-power is as good as the cold-test results at an input power below 120 W. However, the transmission decreases as the input power is further increased. A maximum input power is 210 W with a duty of 18%. The error bars are estimated to be about 5%, which is caused mainly by the fluctuation in the readout of the power meter. The maximal input power is limited by the homemade source. No brush noise or sudden reflection is observed up to the maximal power.

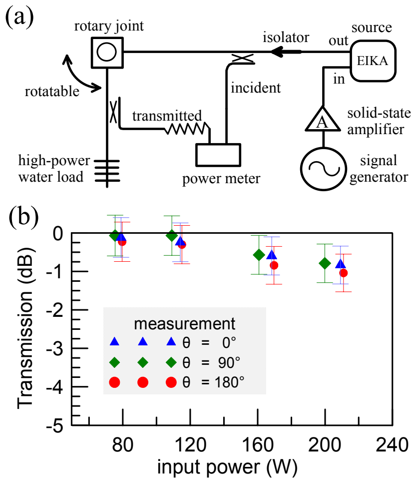

Figure 3 Hot test of the rotary joint. (a) Hot-test circuit. The rf power is provided by a home-made EIA. Incident and transmitted power are measured using a power meter. (b) Measured transmission vs. incident power for three angles.

III. CONCLUSION

Simulations show that the azimuthally symmetric TE_{01} mode is less sensitive to the geometry of the rotary joint and is thus preferred. A high-power Ka-band rotary joint was developed, fabricated, and tested based on two high-quality TE_{01} mode converters. This rotary joint has a low insertion loss (-0.3 dB), is compact (~2.3 λ_g), and has a broad bandwidth (24.3% at a 3-dB transmission). Although both cold test and high-power test all reveal excellent transmission, the reflection (VSWR) is a little bit higher than expected. This is because the authors optimize the transmission not the reflection. The VSWR value can be minimized by further optimizing the power-dividing section. The results show that the rotary joint has a 1-dB transmission loss of 5.7 GHz, centered at 35 GHz (16.8%). The high-power test demonstrates that it can operate at up to 210 W without brush noise or failure.

REFERENCES

[1] T. H. Chang and B. R. Yu, "High-power millimeter-wave rotary joint," Rev. Sci. Instrum. 80, 034701 (2009).